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The vegetation of Chile and the EcoVeg approach in the context of the International Vegetation Classification project

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Abstract

Aims: Chilean vegetation has previously received considerable attention, and several classifications are currently available. The most recent of these was presented for the first time in 2006 and updated in 2017 by the authors. Although widely utilized by researchers both in Chile and Latin America, this information is only available in Spanish, which hampers its usefulness for a broader scientific audience. Here, we provide an overview of the methods and the resulting classification and propose a correspondence between Chilean classification and the International Vegetation Classification (IVC) following the EcoVeg scheme. **Study area:** Continental Chile. **Methods:** Based on the criteria of the EcoVeg approach, we established a linkage of zonal and azonal vegetation units to the macrogroup level and to the formation classes of the IVC. We also generated a map to facilitate crosswalk between the classifications. **Results:** We recognize 23 macrogroups, 13 divisions and 11 formations of zonal vegetation, including three newly proposed macrogroups, one division and one formation. We further recognize 23 macrogroups, 23 divisions and 17 formations of intrazonal vegetation. Together, they encompass all six formation classes of natural vegetation of the IVC. We highlight those units so far not mentioned for Chile in the IVC. Finally, we provide a map of macrogroups and discuss the limitations and prospects of this approach for the classification of Chilean vegetation. **Conclusions:** Chilean zonal vegetation was successfully accommodated in the IVC down to the macrogroup level. The process of linking Chilean zonal vegetation and macrogroups led us to a few suggestions that may be used to improve the IVC.

Taxonomic reference: Zuloaga et al. (2008).

Abbreviations: IVC = International Vegetation Classification

Keywords

crosswalk, formations, macrogroups, vegetation belts, zonal vegetation

Introduction

Chilean vegetation has been subject to several attempts of classification from both floristic and physiognomic points of view (e.g., Reiche 1907; Fuenzalida 1950; Schmithüsen 1956; Oberdorfer 1960; Pisano 1966), but only during the last four decades have some studies provided mapping (Quintanilla 1983; Gajardo 1994; Luebert and Pliscoff 2006a, 2017). These efforts have been primarily motivated by the necessity to establish conservation goals. The

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most recent of these was developed by the authors of this paper, initially as a response to the need of conservation organizations to have a tool to define priorities for the conservation of ecosystems at the national level. In this sense, the classification of vegetation units has been used as a surrogate of ecosystems (Pliscoff and Luebert 2018). Chilean governmental conservation agencies are currently using these vegetation units to identify new protected areas through systematic conservation planning (Luebert and Pliscoff 2010; Pliscoff and Fuentes-Castillo 2011). They have also been employed to assess the effects of climate change on Chilean Ecosystems (Pliscoff et al. 2012; Arroyo et al. 2019; Benavidez-Silva et al. 2021), identifying the impacts on biodiversity of the recent 2017 mega-fires in central Chile (Pliscoff et al. 2020) and to establish categories of ecosystem risk of collapse (Pliscoff 2015; Alaniz et al. 2016; Luebert and Pliscoff 2017; Pliscoff et al. 2019) following the recently developed IUCN guidelines (Rodríguez et al. 2015). This classification has also been utilised as an input in attempts to establish an ecosystem typology at supra-national level (Luebert and Pliscoff 2009; Josse 2014; Keith et al. 2020), and has the potential to be adapted to the EcoVeg classification approach (Faber-Langendoen et al. 2014) aimed at providing an international standard for vegetation classification (Faber-Langendoen et al. 2018, 2020).

However, while widely used in Chile or by Spanish speaking researchers, the usefulness of the classification of Chilean vegetation proposed by Luebert and Pliscoff (2006a, 2017) in an international context is partially hampered by limited readership within a potentially much broader audience (Petorelli et al. 2021). In this context, the purpose of this paper is twofold. We provide an overview of the methods and major features of our classification system (Luebert and Pliscoff 2006a, 2017), then propose a linkage between that classification and the EcoVeg/IVC approach down to macrogroup level (Faber-Langendoen et al. 2014, 2018, 2020). We also generate a map of macrogroups that will facilitate collaboration across borders.

Methods

We used the 2nd edition of the Chilean classification and cartography developed by Luebert and Pliscoff (2017), an overview of which is provided in the Appendix. We first employed coarse vegetation physiognomy and macroclimate to assign each zonal vegetation unit (vegetation belts, see Appendix) to a formation (group level 3 of Faber-Langendoen et al. 2020). We then used the names and description of the vegetation belts to assign each unit to a macrogroup of the EcoVeg classification according to the following criteria (Faber-Langendoen et al. 2014, 2018): biogeography, diagnostic species, growth forms, bioclimate, dynamics, and climate-related hydrology. Information about all criteria is available in the descriptions of the vegetation belts (see Appendix). As a main reference we employed the list of macrogroups of the Americas available in Faber-Langendoen et al. (2018) and complemented it with proposals for new units when considered necessary, following the criteria of Faber-Langendoen et al. (2014). We have chosen the EcoVeg macrogroup level as appropriate for linkage to IVC as the group level is still largely undeveloped in Latin America. However, we consider that Chilean zonal vegetation units may be better accommodated at the EcoVeg group level, which aligns with the NatureServe ecological system types (Josse et al. 2003, 2009).

In addition to zonal vegetation, we established the correspondence between azonal macrogroups and intrazonal units defined in Luebert and Pliscoff (2017) and provide it in Suppl. material 1. These units are currently not mappable and are conceptually broad. The latter is reflected by the fact that, in some cases, one intrazonal unit was assigned to more than one macrogroup or even more than one formation.

Results

We were able to assign all 125 zonal vegetation units to 23 macrogroups in 13 divisions and 11 formations (Table 1). We recognize one new formation (Mediterranean Forest & Woodland) and one new division (Chilean Mediterranean Forest and Woodland) to include the sclerophyllous and deciduous forests that occur in central Chile under Mediterranean-type climate, namely macrogroups M652 (Chilean Mediterranean Sclerophyllous Forest) and M653 (Chilean Mediterranean Deciduous Forest). We further recognize three new macrogroups: 1) Valdivian Temperate Conifer Forest & Woodland within the Cool Temperate Forest & Woodland formation, 2) Magellanian Antiboreal Deciduous Forest and 3) Magellanian Antiboreal Evergreen Forest, both within the Boreal Forest & Woodland formation (Table 1). The first new macrogroup is present in Chile and clearly framed within the Cool Temperate Forest & Woodland formation (1.B.2), but it does not appear as such in the IVC list of macrogroups. The remaining two macrogroups required recognition because our analysis indicates that both evergreen and deciduous Magellanian forests occur under an antiboreal bioclimate, a fact that is not reflected in the IVC classification of macrogroups. The macrogroup map of Chile is depicted in Figure 1 and is available as a shape file through Zenodo (http://dx.doi.org/10.5281/zenodo.4711540).

Four formation classes account for the Chilean zonal vegetation:

1. Forest & Woodland

This formation class is distributed in central and southern Chile and includes a variety of bioclimatic conditions, from Mediterranean-type to cold antiboreal. Vegetation ranges from sclerophyllous to deciduous, lauriphyllous and evergreen forests. It is divided into three formations (1.B.2. Cool Temperate Forest & Woodland, 1.B.4. Boreal Forest & Woodland, 1.B.6. Mediterranean Forest &

Table 1. Formations, divisions and macrogroups represented in the Chilean zonal vegetation. The left-hand column indicates the assignment of zonal units of Luebert and Pliscoff (2017) to each macrogroup. Macrogroup codes with asterisks indicate new macrogroups proposed here (different numbers of asterisks code distinguish newly proposed macrogroups for a clear link to Table A1). Division 1.B.6. is also indicated with an asterisk, because it is a new division proposed here. A full list of Chilean zonal units is given in Table A1.

Chilean zonal units	Macrogroup	Division	Formation
P71–P73, P81–P84	M655. Valdivian Lower Montane Evergreen Forest	D241. Valdivian Cool Temperate Forest	1.B.2. Cool Temperate Forest & Woodland
P54–P60	M656. Valdivian Lower Montane Deciduous Forest		
P61–P65, P67–P69	M657. Valdivian Montane & Upper Montane Deciduous Forest		
P85–P88	M658. Valdivian Montane & Upper Montane Evergreen Forest		
P74–P80, P92	***Valdivian Temperate Conifer Forest & Woodland		
P66, P70	*Magellanian Antiboreal Deciduous Forest	D247. Magellanian Antiboreal Forest	1.B.4. Boreal Forest & Woodland
P89–P91	**Magellanian Antiboreal Evergreen Forest		
P38–P45	M652. Chilean Mediterranean Sclerophyllous Forest	Chilean Mediterranean Forest and Woodland*	1.B.6. Mediterranean Forest & Woodland*
P46–P53	M653. Chilean Mediterranean Deciduous Forest		
P34,P36	M741. Central Chilean Coastal Scrub	D273. Chilean Mediterranean Scrub, Grassland & Forb Meadow	2.B.1. Mediterranean Scrub & Grassland
P27,P28,P32,P33,P35,P37	M742. Central Chilean Interior Scrub		
P122–P125	M750. Patagonian Mesic Grassland & Shrubland	D144. Patagonian Grassland & Shrubland	2.B.2. Temperate Grassland & Shrubland
P93	M758. Southern Andean Montane Bog	D282. Southern Andean Montane Bog	2.C.2. Temperate to Polar Bog & Fen
P94–P96	M759. Magellanian Anti-Boreal Bog & Fen	D283. Magellanian Bog & Fen	
P5, P29	M740. South American Pacific Desert Salt Flats	D272. South American Pacific Desert Salt Flats	2.C.5. Salt Marsh
P30	M782. Sechura Atacama Semi-Desert Riparian Scrub	D294. South American Pacific Semi-Desert Scrub & Grassland	3.A.2. Warm Desert & Semi-Desert Scrub & Grassland
P1–P4,P6,P22–P24	M783. Sechura Atacama Semi-Desert Scrub		
P7–P11,P13,P14,P17,P21	M784. Chilean Mediterranean Coastal Semi-Desert Scrub & Grassland		
P12,P15,P16,P18–P20,P25,P26,P31	M785. Chilean Mediterranean Interior Semi-Desert Scrub & Grassland		
P110–P113,P118,P119	M788. Mediterranean Andean Cool Semi-Desert Scrub & Grassland	D296. Mediterranean Southern Andean Cool Semi-Desert Scrub & Grassland	3.B.1. Cool Semi-Desert Scrub & Grassland
P97–P109,P117	M794. High Andean Xeric Puna Bunch Grassland	D298. Tropical & Mediterranean Andean High Montane Scrub & Grassland	4.A.1. Tropical High Montane Scrub & Grassland
P114,P115,P120	M795. Southern Andean Alpine Tundra	D299. Southern Andean High Montane Tundra	4.B.1 Temperate & Boreal Alpine Tundra
P116, P121	M796. Magellanian Montane Tundra	D300. Magellanian High Montane Tundra	

Woodland) and includes ten macrogroups to which 55 zonal units have been assigned (Table 1).

2. Shrub & Herb Vegetation

This formation class is discontinuously distributed in the Mediterranean zone of central Chile, in the extreme north and in both eastern and western Patagonia, also under a variety of climatic influences. In Chile, vegetation varies form thorny shrublands to Patagonian grasslands and moorlands. We identified four formations of zonal vegetation (2.B.1. Mediterranean Scrub & Grassland, 2.B.2. Temperate Grassland & Shrubland, 2.C.2. Temperate to Polar Bog & Fen, 2.C.5. Salt Marsh). However, the latter two may be considered as azonal since they are strongly influenced by edaphic conditions, but they occupy large geographical extensions that make them mappable. Within these formations, 18 zonal units were assigned to six macrogroups (Table 1).

3. Desert & Semi-Desert

These are distributed in northern Chile under both Tropical and Mediterranean influences. They include the absolute desert as well as xeromorphic scrub and forb vegetation. Two formations were identified here (3.A.2. Warm Desert & Semi-Desert Scrub & Grassland, 3.B.1. Cool Semi-Desert Scrub & Grassland). High-Andean vegetation of the Mediterranean zone of central Chile falls within this formation class. It includes 33 zonal units assigned to five macrogroups (Table 1).

4. Polar & High Montane Scrub, Grassland & Barrens

Distributed along the high mountains from northernmost Chile, under Tropical bioclimate, to the southernmost portion of the country, under antiboreal

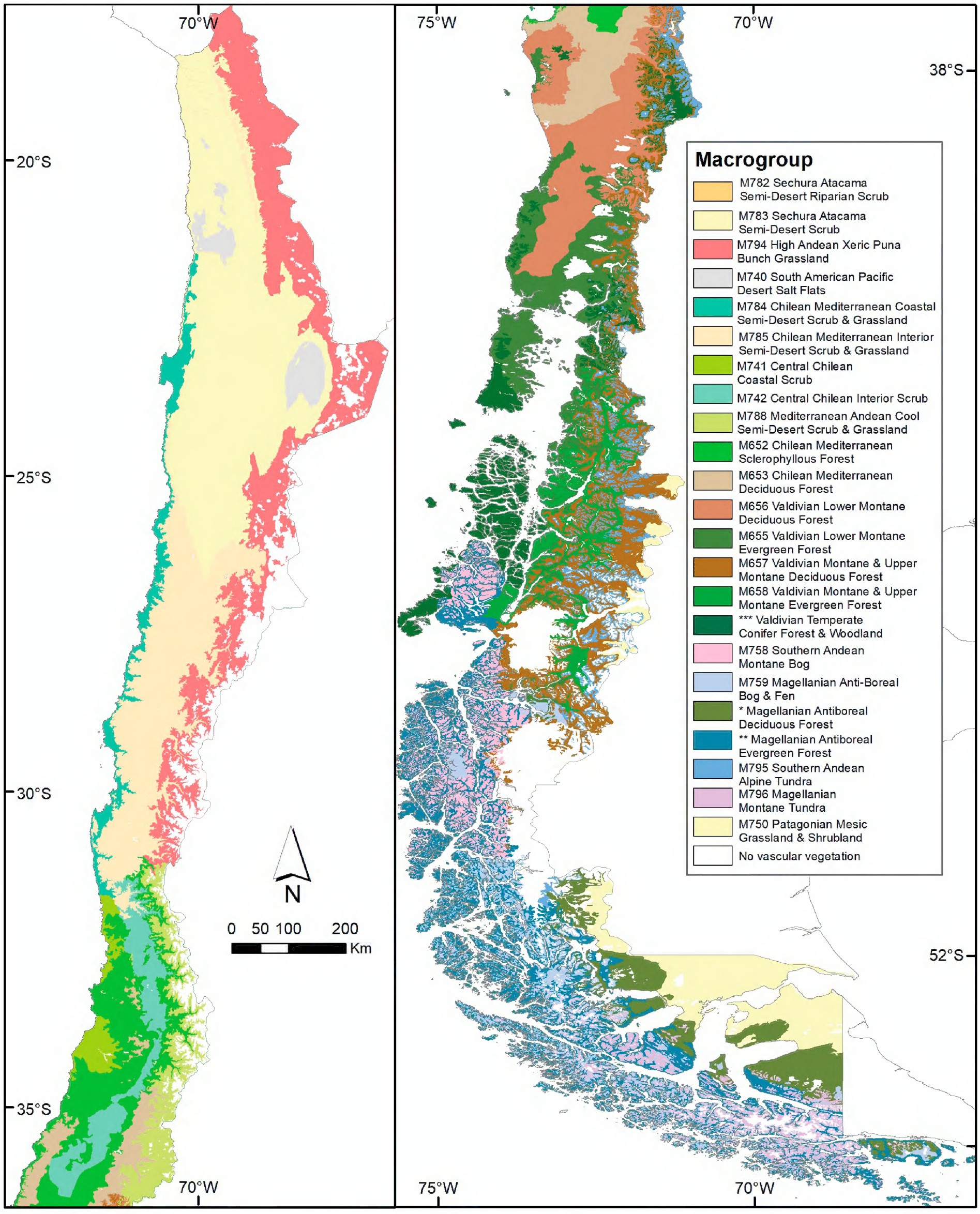

Figure 1. Map of Chilean macrogroups as a result of linkages established for the zonal vegetation units of Luebert and Pliscoff (2017). This map is available as shapefile at the Zenodo repository (http://dx.doi.org/10.5281/zenodo.4711540).

bioclimate. Scrub, grasslands, and forb vegetation are included in this formation class, corresponding to two formations (4.A.1. Tropical High Montane Scrub & Grassland, 4.B.1 Temperate & Boreal Alpine Tundra). Nineteen zonal units were assigned to three macrogroups (Table 1).

Intrazonal vegetation units were provisionally assigned to 23 macrogroups classified in 23 divisions and

17 formations (Suppl. material 1). However, some of these assignments are doubtful (marked with question marks in the table), mostly due to the broadness of our intrazonal units combined with a lack of detailed descriptions of these macrogroups. Apart from the formation classes described above for zonal vegetation, two further classes account for intrazonal vegetation units:

5. Aquatic Vegetation

Distributed across bioclimatic domains, aquatic vegetation can be found throughout the Chilean territory. It includes floating, natant and submerged vegetation units as well as semi-aquatic grasslands and forb vegetation, and forb vegetation of ephemeral wetlands.

6. Open Rock Vegetation

This formation class is also ubiquitous and distributed across the country with relative independence of bioclimatic conditions. It encompasses coastal vegetation of rocks and cliffs, high-Andean and low-elevation inland rupicolous vegetation as well as vegetation of landslides and caves.

Discussion

We found the assignment of the zonal vegetation units of Luebert and Pliscoff (2017) to the EcoVeg macrogroups straightforward based on the criteria of Faber-Langendoen et al. (2014, 2018). The major difficulty was in the overlap between macroclimates and biogeographical units used for the hierarchical classification at the level of formations and divisions of the IVC project: while macroclimatic criteria are more important at the level of formation, divisions are defined in terms of biogeography (Faber-Langendoen et al. 2014, 2018). For example, Valdivian forests tend to be correlated to the temperate macroclimate while Magellanian forests are mostly within the antiboreal macroclimate (Schmithüsen 1956; Luebert and Pliscoff 2005; Tecklin et al. 2011). Some zonal units characterized by similar physiognomy and dominant species are distributed across two macroclimates. One of the problems is perhaps that the IVC does not explicitly advise the bioclimatic classification system that should be employed and applied to its units. Because macroclimate is a classification criterion at a higher hierarchical level (i.e., formations), similar physiognomies distributed across temperate and antiboreal bioclimates were assigned to different divisions according to biogeography. Macrogroups were then recognized on the basis of growth forms and dominant species. This is the case of *Nothofagus pumilio*- and *N. betuloides*-dominated forests, which are distributed across temperate and antiboreal bioclimates (Amigo and Rodríguez-Guitián 2011), classified in Valdivian and Magellanian forests, respectively, at the level of division, and into deciduous and evergreen forests at the level of macrogroup.

On the other hand, our plant formations (Luebert and Pliscoff 2017) do not fully align with IVC formations. This lack of correspondence may be due to distinct criteria to define formations in both classification systems. While formations in both systems are largely physiognomic-ecological units (Luebert and Pliscoff (2017) applied the classification of Ellenberg and Mueller-Dombois (1967) practically unchanged to the Chilean vegetation), IVC formations incorporate a variety of previous classification systems to construct the classification of plant formations (Faber-Langendoen et al. 2014, 2018). Navarro and Molina (2021) emphasize the necessity of a standardized, consistent and unambiguous designation system of formations in the IVC classification, at least for the Neotropics.

Few of the macrogroups mentioned for Chile by Faber-Langendoen et al. (2018) were not assigned to any of our Chilean vegetation units. This is due to a variety of reasons, as follows. M659 Magellanian Temperate Evergreen Forest: Magellanian evergreen forests are all antiboreal and were therefore included in a newly proposed macrogroup (Table 1); M722 Andean Puna Wet Meadow: We do not know exactly to which vegetation type this macrogroup refers; however, Andean Puna wet vegetation reported for Chile in our classification appears to be associated only with riparian units (M863, Suppl. material 1) or bogs (M708, Suppl. material 1); M761 Southern Andean Montane Salt Marsh: We do not know of any report of Southern Andean Salt Marshes present in Chile; M769 Central Andean Xeromorphic Scrub & Woodland: This unit appears to be present in Peru and Bolivia, but absent in Chile, where Interandean Valley Xeromorphic Scrub & Woodland (D289) are frequently reported; M861 Sechura Atacama Semi-Desert Cliff & Pavement: We are not aware of reports of this vegetation type in Chile and so it is not included in our classification system; M787 Xeric Puna Succulent Scrub: This unit is present in Chile, represented by locally abundant *Trichocereus atacamensis*-dominated vegetation (Villagrán et al. 1981), but embeded in the high-elevation portions of Sechura Atacama Semi-Desert Scrub (M783) and the High Andean Xeric Puna Bunch Grassland (M794).

The use of a biogeographical unit in the IVC that includes both Atacama and Peruvian (Sechura) deserts may be contentious since they have been reported to be floristically very different (Rundel et al. 1991; Pinto and Luebert 2009). However, these studies are concentrated on the coastal range (i.e., the so-called lomas formations), while these deserts extend beyond coastal areas in several divergent definitions found in the literature (e.g., Rauh 1985; Rundel et al. 1991; Luebert 2011). Phylogenetic studies compiled by Luebert (2011) do show that there are biogeographical relationships between the Atacama and Peruvian deserts and that these relationships may have

originated through an Andean connection rather than a coastal one. The latter was confirmed in a recent floristic comparison of the Atacama and Peruvian deserts including both coastal and Andean localities (Ruhm et al. 2020) and is reflected in the biogeographical classification proposed by Rivas-Martínez et al. (2011), which is the approach followed here regarding this region.

Two IVC formations occurring in Chile (1.B.4 and 4.B.1, see Table 1) include the terms "Boreal" and "Alpine". As discussed elsewhere (e.g., Tuhkanen et al. 1990; Tuhkanen 1992; Richter 2001; Rivas-Martínez et al. 2003), these terms may not be appropriate for southern hemisphere vegetation. We suggest that the naming of these and other IVC formations potentially having this problem be revised to make it globally applicable.

Macroclimatic criteria do not seem to be hierarchically consistent between different formations in the classification of Faber-Langendoen et al. (2018). On one hand, the Tropical & Mediterranean Andean High Montane Scrub & Grassland division is included in the Tropical High Montane Scrub & Grassland formation. However, the latter formation only includes South American macrogroups of Puna and Paramo, thus Mediterranean High-Andean scrubs and grasslands are better included within the Cool Semi-Desert Scrub & Grassland formation (3.B.1, see Table 1) in the absence of a specific macrogroup dedicated to this vegetation within the formation class of Polar & High Montane Scrub, Grassland & Barrens of Faber-Langendoen et al. (2018). On the other hand, Mediterranean forests, woodlands, scrubs, and grasslands are included within Temperate units at different levels: Mediterranean scrubs and grasslands are defined at the formation level within a formation class of Temperate scrubs and grasslands; Mediterranean forests and woodlands are not defined at any level but included within the Warm Temperate Forest & Woodland formation, which currently includes a mix of sclerophyllous and deciduous forests. For the latter we proposed the recognition of a new formation of Mediterranean forests and woodlands (see above). A division of Chilean Mediterranean Forest and Woodland should thus replace current Chilean Warm Temperate Forest & Woodland (D239). Biogeographically, this division is clearly justified in terms of its floristic differentiation from other portions of the Chilean territory based on both floristic composition (Bannister et al. 2012) and phylogenetic diversity (Scherson et al. 2017). This new formation may also include at least part of the Californian Forest & Woodland division (D007), which occurs under a Mediterranean-type bioclimate, and perhaps other forest and woodland vegetation units in the Mediterranean basin, South Africa and Australia. Here it is worthwhile noting that the definition of a Mediterranean bioclimate by Rivas-Martínez (1993, 2005, 2010) employed in Luebert and Pliscoff (2006a, 2017) may differ from other definitions of Mediterranean, both in its hierarchical position and in its spatial extension. In the classification of Rivas-Martínez (1993, 2005, 2010), the Mediterranean bioclimate is simply defined as a seasonal bioclimate with cold and humid winters and warm and dry summers with a dry season of at least two months. In other climatic classification systems (such as that of Köppen; see Peel et al. 2007), the Mediterranean is part of the Temperate. Conversely, the definition employed here includes areas otherwise considered as both deserts and steppes (for a comparison applied to the Chilean case see Luebert and Pliscoff 2006b), corresponding to the Rivas-Martínez's approach.

We found that the *Nothofagus antarctica*-dominated units were difficult to assign to a formation. We decided to include them in forest formations, though this species often grows as a large shrub or small tree and determines vegetation physiognomy (Veblen et al. 1996). No formation dominated by arborescent plants has been defined at the macrogroup level, and accommodating these units in a new macrogroup may imply major rearrangements of the IVC classification.

Finally, we did not find any macrogroup category to include moorlands. In the authors' scheme (units P93–P96 in Table A1) moorlands represent a formation dominated by shrub and herbaceous species on water-saturated soils, distributed zonally and covering extensive coastal and interior lowlands in the archipelagos and islands of southern Chile. The most appropriate assignment, used here, would be the macrogroups Southern Andes montane bog (M758) and Magellanian anti-boreal bog & fen (M759), but these units seem to be more closely related to azonal wetlands present in Andean montane areas under the formation of Temperate to Polar Bog & Fen (2.C.2., see Table 1). Nevertheless, since these moorlands constitute the dominant element of the landscape across extensive regions of southern Chile, their inclusion in the above-mentioned macrogroup, regardless of zonal or azonal character, should not represent a major problem.

Chilean zonal vegetation could largely be fitted into macrogroups using the criteria of the EcoVeg approach. Proposed new units and the above-mentioned problems and drawbacks may serve as material for refinements and further discussion about the International Vegetation Classification. Phytosociological units so far identified for Chile (mostly based on the seminal work of Oberdofer 1960), which are part of the data baseline for our identification of zonal vegetation units (see Appendix below), can also be directly translated into IVC units down to association level. A first attempt at accomplishing this task is currently under review in this journal (Álvarez and Luebert, submitted). This may also serve to include secondary/degraded and ruderal vegetation, which is not addressed in our classification system.

Despite numerous works dealing with intrazonal vegetation in Chile, we have not yet achieved a satisfactory and hierarchically consistent classification (see Luebert and Pliscoff 2017). This is reflected in some of these units being both climatically and biogeographically quite broad (thus assigned to more than one macrogroup) and in some doubtful assignments, five of which are not mentioned for

Chile by Faber-Langendoen et al. (2018; see Suppl. material 1). Therefore, our assignments of intrazonal units to macrogroups must be regarded as preliminary. The description and classification of intrazonal vegetation is perhaps one of the major pending challenges in the study of Chilean vegetation.

Data availability

Original data are available through the Zenodo repository (http://dx.doi.org/10.5281/zenodo.60800). Results from the present study are also available through Zenodo (http://dx.doi.org/10.5281/zenodo.4711540).

Author contributions

Both authors conceived the idea and analyzed the data. FL drafted the manuscript with contributions of PP.

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Appendix 1

Overview of authors' classification of Chilean vegetation

The classification of Chilean vegetation by the authors was originally published in 2006 (Luebert and Pliscoff 2006a; hereafter 1st edition) and extensively revised roughly a decade later (Luebert and Pliscoff 2017; hereafter 2nd edition). The general approach consisted of combining the spatial information about vegetation physiognomy, dominant species and bioclimate. Spatial information on vegetation physiognomy was mainly sourced from Gajardo (1994), for which a digital map was available prior to generating the data for the 1st edition. Gajardo's (1994) vegetation units were reclassified according to the criteria of Ellenberg and Mueller-Dombois (1967) at the formation class and formation levels. This was then complemented with a bibliographic revision on Chilean vegetation; the 2nd edition of the classification cited a total of 1701 references, most of which include vegetation descriptions with various levels of complexity. A spatial systematization of this information through georeferencing of vegetation descriptions that included physiognomy and dominant species (see Luebert and Pliscoff 2009) was used in the 2nd edition to refine unit boundaries from the map generated in the 1st edition. Bioclimate was used, applying the classification of Rivas-Martínez (1993, 2005, 2010), to identify macrobioclimates, bioclimates, thermotypes, ombrotypes and continentality types. These bioclimatic units are largely based on mean, maximum and minimum temperatures (T, M, m, Tmin, Tmax), the thermicity index (It, Itc), positive temperature (Tp), mean annual precipitation (P), the ombrothermic index (Io, Ios_2), Potential Evapotranspiration (ETP), and the continentality index (Ic), all defined and explained in Rivas-Martínez (1993, 2005, 2010) and in Luebert and Pliscoff (2006a, 2017).

Based on that information, we aimed to identify breaks in dominant species along elevation gradients correlated to changes in bioclimate within each vegetation formation. To this end, we used the combination of thermotypes and ombrotypes (bioclimatic belts, according to Rivas-Martínez) and the spatial location of vegetation descriptions available in the literature (0.5 degree latitudinal bands) and elevation. As a result, we recognized basic units of zonal vegetation that we called "vegetation belts" (because they correspond to the combination of vegetation features and bioclimatic belts), operationally defined as follows: "space characterized by a set of zonal plant communities with uniform structure and physiognomy, located under homogeneous mesoclimatic conditions (bioclimatic belts) that occupy a defined position along an elevation gradient, at a given spatial and temporal scale".

Apart from the map mentioned above of plant formations derived from Gajardo (1994), we used a Digital Elevation Model (DEM) to identify spatial changes in dominant species (as reported in the literature) along the elevation gradient, climatic surfaces at 1 km resolution and information from georeferenced climate stations compiled from different sources, especially (Hajek and di Castri 1975; FAO 1985, 2001; INIA 1989). While the DEM used in the 1st edition (Rabus et al. 2003) was highly inaccurate for the southernmost portion of Chile, especially on the Pacific coastal Patagonia, the 2nd edition benefited from a highly improved version (Farr et al. 2007) that enabled better unit delimitations in that zone. Likewise, we employed climate surfaces from Worldclim version 1 (Hijmans et al. 2005) to spatialize bioclimatic units for the 1st edition, while in the 2nd edition we used improved climatic surfaces for Chile and adjacent regions (Pliscoff et al. 2014) based on an analysis of a larger number of climate stations but using the same interpolation method as Worldclim. Anusplin v.4.36 (Hutchinson 2006; Xu and Hutchinson 2013) was employed to do this, implementing the methods described by Hutchinson (1995).

Based on the spatial information described above and the data available in the literature, a classification of vegetation belts was generated heuristically by systematically revising longitudinal and elevational changes in vegetation physiognomy, dominant species

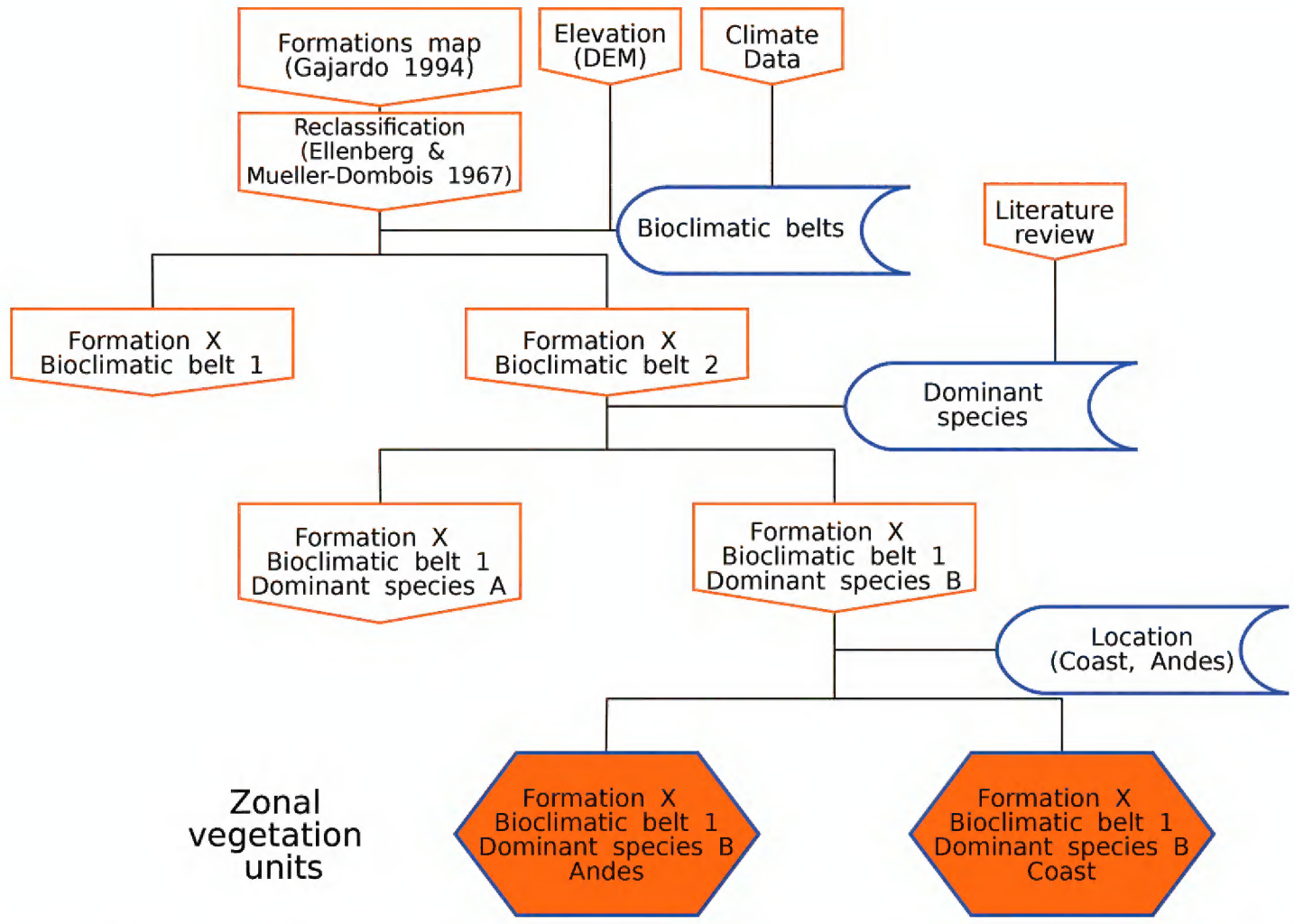

Figure A1. Flowchart depicting the methodology employed for the identification of zonal vegetation units by Luebert and Pliscoff (2006a, 2017).

and bioclimate for each latitudinal band of 0.5 degrees. Each unit was designated according to its physiognomy, dominant species, macroclimate and geographic location (i.e., coastal, interior, Andean). All GIS-data was processed in Arcgis v.10.3 (ESRI 2014) and the R-package raster v. 2.8-19 (Hijmans 2016). Figure A1 depicts the sequence of steps that were used for the identification of zonal vegetation units.

In the 1st edition, 127 vegetation belts were recognized. They were grouped in 17 vegetation formations and six formation classes. As a result of growing literature, systematization of spatial information and the use of different climatic surfaces, the 2nd edition recognized 125 vegetation belts grouped in 19 vegetation formations and six formation classes (Table A1). These changes were not merely due to the removal of two units but the result of various re-arrangements. These included the addition of two new formations (Dunes of aerophytes and Ephemeral forb vegetation) and their respective vegetation belts, and the grouping of other units and refinements of the spatial boundaries between units using previously compiled georeferenced point data (Luebert and Pliscoff 2009). The latest version of the map of plant formations is depicted in Figure A2. Each vegetation belt is described in terms of physiognomy, combination of dominant and common species, included communities (zonal, intrazonal and extrazonal), floristic composition, dynamics, geographical distribution, bioclimatic indices and bibliographic references. In the nomenclature of zonal units we adopted the dash (-) or slash (/) distinction to indicate whether the dominant species belong to the same or to different strata, respectively, as proposed by Faber-Langendoen et al. (2014).

In addition to changes in the classification of zonal vegetation, the 2nd edition also proposed a classification of extra- and intrazonal vegetation units based on a literature review and georeferencing point data. The 22 extrazonal units are included within each formation. Intrazonal vegetation included 31 basic units grouped into seven major categories: aquatic vegetation, coastal vegetation, halophilous vegetation, lacustrine vegetation, peats and bogs, riparian vegetation and rupicolous vegetation. Both extra- and intrazonal units are spatially embedded in the zonal units. We have employed the term intrazonal vegetation following Ivan (1979), who suggests that this term is preferable to azonal vegetation due to the difficulty in finding vegetation units occurring with absolute independence from the regional climate. In other classification systems (e.g., Ellenberg 1996; Breckle and Walter 2002), azonal vegetation units include what is here called intrazonal vegetation. Mucina et al. (2016) make a difference between intrazonal and azonal vegetation, the latter having a distribution across more than one biome. This differentiation suggests that the recognition of azonal units may depend on the spatial scale at which these units are defined and may thus be applicable at global and continental scales, but not necessarily at the level of one country like Chile. Finally, extrazonal vegetation is here understood as vegetation types that, having a zonal distribution in one region, occur beyond that zonal range due to the influence of local (largely substrate) conditions (Ellenberg 1996).

Both editions include an analysis of conservation based on the representativeness of each vegetation belt in the Chilean protected area system and an estimation of the proportion of each vegetation belt replaced by anthropogenic land uses (agriculture, forestry plantations, urban areas, industrial and mining areas). The 2nd edition also includes an

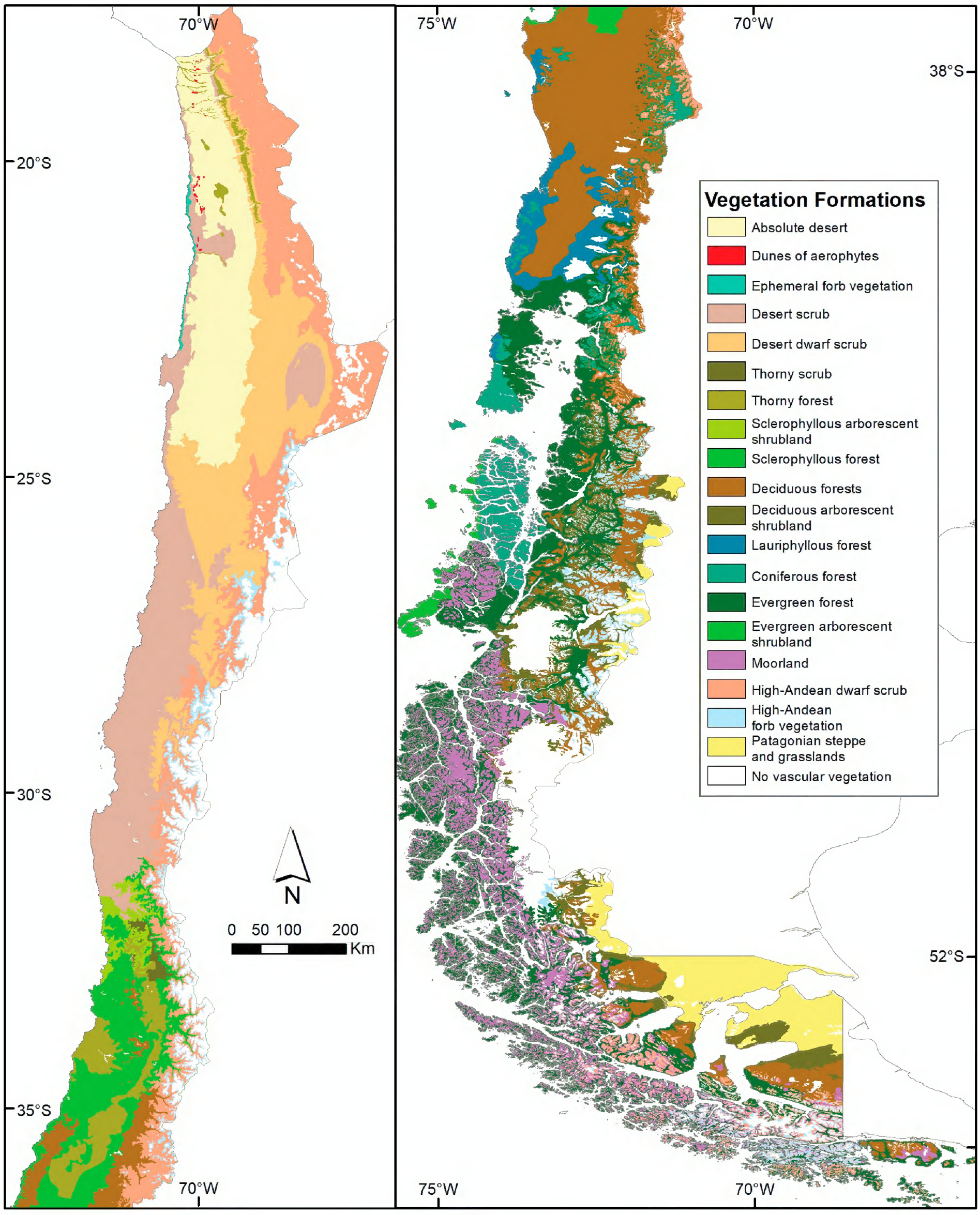

Figure A2. Map of Chilean formations of zonal vegetation as defined in Luebert and Pliscoff (2017). This map is available as shapefile at the Zenodo repository (http://dx.doi.org/10.5281/zenodo.60800).

analysis for risk of collapse based on the IUCN criteria (Rodríguez et al. 2015) and an estimation of the potential effects of climate change on the area and distribution of each vegetation belt based on future climate change scenarios.

Vegetation and bioclimatic classification maps of the 2nd edition are freely available in digital form (shapefiles) through the Zenodo repository (https://doi.org/10.5281/zenodo.60800) along with the full list of references in BibTeX format and data tables including georeferenced point data and statistics relative to the surface, representativeness in the protected area system, risk of collapse and potential effects of climate change.

Table A1. List of the formations (in bold) and zonal units of Luebert and Pliscoff (2017) with unit codes (P1–P125) and corresponding IVC macrogroup and formation codes (in brackets; see also Table 1).

Absolute desert

P1. Tropical interior desert with sparse vegetation (M783, 3.A.2)

Dunes of aerophytes

P2. Tropical coastal dunes of *Tillandsia landbeckii - T. marconae* (M783, 3.A.2)

Ephemeral forb vegetation

P3. Tropical coastal ephemeral forb vegetation of *Nolana adansonii - N. lycioides* (M783, 3.A.2)

Desert scrub

P4. Tropical interior desert scrub of *Malesherbia auristipulata - Tarasa operculata* (M783, 3.A.2)
P5. Tropical interior desert scrub of *Atriplex atacamensis - Tessaria absinthioides* (M740, 2.C.5)
P6. Tropical coastal desert scrub of *Nolana sedifolia / Eulychnia iquiquensis* (M783, 3.A.2)
P7. Tropical-Mediterranean coastal desert scrub of *Ephedra breana / Eulychnia iquiquensis* (M784, 3.A.2)
P8. Tropical-Mediterranean coastal desert scrub of *Copiapoa boliviana - Heliotropium pycnophyllum* (M784, 3.A.2)
P9. Mediterranean coastal desert scrub of *Gypothamnium pinifolium - Heliotropium pycnophyllum* (M784, 3.A.2)
P10. Mediterranean coastal desert scrub of *Euphorbia lactiflua / Eulychnia iquiquensis* (M784, 3.A.2)
P11. Mediterranean coastal desert scrub of *Euphorbia lactiflua / Eulychnia saint-pieana* (M784, 3.A.2)
P12. Mediterranean interior desert scrub of *Oxyphyllum ulicinum - Gymnophyton foliosum* (M785, 3.A.2)
P13. Mediterranean coastal desert scrub of *Heliotropium floridum - Atriplex clivicola* (M784, 3.A.2)
P14. Mediterranean coastal desert scrub of *Oxalis virgosa / Eulychnia breviflora* (M784, 3.A.2)
P15. Mediterranean interior desert scrub of *Skytanthus acutus - Atriplex deserticola* (M785, 3.A.2)
P16. Mediterranean interior desert scrub of *Huidobria chilensis - Nolana leptophylla* (M785, 3.A.2)
P17. Mediterranean coastal desert scrub of *Oxalis virgosa - Heliotropium stenophyllum* (M784, 3.A.2)
P18. Mediterranean interior desert scrub of *Adesmia argentea - Bulnesia chilensis* (M785, 3.A.2)
P19. Mediterranean interior desert scrub of *Heliotropium stenophyllum - Flourensia thurifera* (M785, 3.A.2)
P20. Mediterranean interior desert scrub of *Flourensia thurifera - Colliguaja odorifera* (M785, 3.A.2)
P21. Mediterranean coastal desert scrub of *Bahia ambrosioides / Puya chilensis* (M784, 3.A.2)

Desert dwarf scrub

P22. Tropical interior desert dwarf scrub of *Adesmia atacamensis - Cistanthe salsoloides* (M783, 3.A.2)
P23. Tropical Andean desert dwarf scrub of *Atriplex imbricata - Acantholippia deserticola* (M783, 3.A.2)
P24. Tropical interior desert dwarf scrub of *Nolana leptophylla - Cistanthe salsoloides* (M783, 3.A.2)
P25. Tropical-Mediterranean Andean desert dwarf scrub of *Atriplex imbricata* (M785, 3.A.2)
P26. Mediterranean Andean desert dwarf scrub of *Senecio proteus - Haplopappus baylahuen* (M785, 3.A.2)

Thorny scrub

P27. Mediterranean interior thorny scrub of *Trevoa quinquinervia - Colliguaja odorifera* (M742, 2.B.1)
P28. Mediterranean interior thorny scrub of *Puya coerulea - Colliguaja odorifera* (M742, 2.B.1)

Thorny forest

P29. Tropical interior thorny forest of *Prosopis tamarugo / Tessaria absinthiodes* (M740, 2.C.5)
P30. Tropical interior thorny forest of *Geoffroea decorticans - Prosopis alba* (M782, 3.A.2)
P31. Tropical Andean thorny forest of *Browningia candelaris - Corryocactus brevistylus* (M785, 3.A.2)
P32. Mediterranean interior thorny forest of *Acacia caven - Prosopis chilensis* (M742, 2.B.1)
P33. Mediterranean Andean thorny forest of *Acacia caven / Baccharis paniculata* (M742, 2.B.1)
P34. Mediterranean coastal thorny forest of *Acacia caven - Maytenus boaria* (M741, 2.B.1)
P35. Mediterranean interior thorny forest of *Acacia caven - Lithrea caustica* (M742, 2.B.1)

Sclerophyllous arborescent shrubland

P36. Mediterranean coastal sclerophyllous arborescent shrubland of *Peumus boldus - Schinus latifolius* (M741, 2.B.1)
P37. Mediterranean interior sclerophyllous arborescent shrubland of *Quillaja saponaria / Porlieria chilensis* (M742, 2.B.1)

Sclerophyllous forest

P38. Mediterranean Andean sclerophyllous forest of *Kageneckia angustifolia / Guindilia trinervis* (M652, 1.B.6)
P39. Mediterranean coastal sclerophyllous forest of *Cryptocarya alba - Peumus boldus* (M652, 1.B.6)
P40. Mediterranean coastal sclerophyllous forest of *Lithrea caustica - Cryptocarya alba* (M652, 1.B.6)
P41. Mediterranean Andean sclerophyllous forest of *Quillaja saponaria - Lithrea caustica* (M652, 1.B.6)
P42. Mediterranean coastal sclerophyllous forest of *Lithrea caustica - Azara integrifolia* (M652, 1.B.6)
P43. Mediterranean interior sclerophyllous forest of *Lithrea caustica - Peumus boldus* (M652, 1.B.6)
P44. Mediterranean Andean sclerophyllous forest of *Lithrea caustica - Lomatia hirsuta* (M652, 1.B.6)
P45. Mediterranean interior sclerophyllous forest of *Quillaja saponaria / Fabiana imbricata* (M652, 1.B.6)

Deciduous forests

P46. Mediterranean coastal deciduous forest of *Nothofagus macrocarpa / Ribes punctatum* (M653, 1.B.6)
P47. Mediterranean interior deciduous forest of *Nothofagus obliqua - Cryptocarya alba* (M653, 1.B.6)
P48. Mediterranean-Temperate Andean deciduous forest of *Nothofagus obliqua - Austrocedrus chilensis* (M653, 1.B.6)
P49. Mediterranean coastal deciduous forest of *Nothofagus glauca - Azara petiolaris* (M653, 1.B.6)
P50. Mediterranean coastal deciduous forest of *Nothofagus glauca - Persea lingue* (M653, 1.B.6)
P51. Mediterranean Andean deciduous forest of *Nothofagus glauca - N. obliqua* (M653, 1.B.6)
P52. Mediterranean coastal deciduous forest of *Nothofagus obliqua - Gomortega keule* (M653, 1.B.6)
P53. Mediterranean deciduous forest of *Nothofagus obliqua - Persea lingue* (M653, 1.B.6)
P54. Temperate deciduous forest of *Nothofagus obliqua - Laurelia sempervirens* (M656, 1.B.2)
P55. Mediterranean-Temperate coastal mixed of *Nothofagus dombeyi - N. obliqua* (M656, 1.B.2)
P56. Temperate coastal deciduous forest of *Nothofagus alpina - Persea lingue* (M656, 1.B.2)
P57. Mediterranean-Temperate Andean deciduous forest of *Nothofagus alpina - N. obliqua* (M656, 1.B.2)
P58. Temperate Andean deciduous forest of *Nothofagus alpina - Dasyphyllum diacanthoides* (M656, 1.B.2)
P59. Temperate Andean deciduous forest of *Nothofagus alpina - N. dombeyi* (M656, 1.B.2)
P60. Mediterranean-Temperate Andean deciduous forest of *Nothofagus pumilio - N. obliqua* (M656, 1.B.2)

P61. Temperate Andean deciduous forest of *Nothofagus pumilio - Araucaria araucana* (M657, 1.B.2)
P62. Temperate Andean deciduous forest of *Nothofagus pumilio / Drimys andina* (M657, 1.B.2)
P63. Temperate Andean deciduous forest of *Nothofagus pumilio / Berberis ilicifolia* (M657, 1.B.2)
P64. Temperate Andean deciduous forest of *Nothofagus pumilio / Azara alpina* (M657, 1.B.2)
P65. Temperate Andean deciduous forest of *Nothofagus pumilio / Ribes cucullatum* (M657, 1.B.2)
P66. Temperate-Antiboreal Andean deciduous forest of *Nothofagus pumilio / Maytenus disticha* (*, 1.B.4)

Deciduous arborescent shrubland

P67. Temperate Andean deciduous shrubland of *Nothofagus antarctica* (M657, 1.B.2)
P68. Temperate Andean deciduous shrubland of *Nothofagus antarctica / Empetrum rubrum* (M657, 1.B.2)
P69. Mediterranean-Temperate eastern deciduous shrubland of *Nothofagus antarctica / Berberis microphylla* (M657, 1.B.2)
P70. Temperate-Antiboreal Andean deciduous shrubland of *Nothofagus antarctica / Chiliotrichum diffusum* (*, 1.B.4)

Lauriphyllous forest

P71. Temperate coastal lauriphyllous forest of *Aextoxicon punctatum - Laurelia sempervirens* (M655, 1.B.2)
P72. Temperate coastal lauriphyllous forest of *Weinmannia trichosperma - Laureliopsis philippiana* (M655, 1.B.2)
P73. Temperate interior lauriphyllous forest of *Nothofagus dombeyi - Eucryphia cordifolia* (M655, 1.B.2)

Coniferous forest

P74. Temperate coastal coniferous forest of *Araucaria araucana* (***, 1.B.2)
P75. Temperate Andean coniferous forest of *Araucaria araucana - Nothofagus dombeyi* (***, 1.B.2)
P76. Mediterranean-Temperate Andean coniferous forest of *Araucaria araucana / Festuca scabriuscula* (***, 1.B.2)
P77. Temperate coastal coniferous forest of *Fitzroya cupressoides* (***, 1.B.2)
P78. Temperate Andean coniferous forest of *Fitzroya cupressoides* (***, 1.B.2)
P79. Temperate coastal coniferous forest of *Pilgerodendron uvifera - Tepualia stipularis* (***, 1.B.2)
P80. Temperate coastal coniferous forest of *Pilgerodendron uvifera / Astelia pumila* (***, 1.B.2)

Evergreen forest

P81. Temperate Andean evergreen forest of *Nothofagus dombeyi / Gaultheria phillyreifolia* (M655, 1.B.2)
P82. Temperate Andean evergreen forest of *Nothofagus dombeyi - Saxegothaea conspicua* (M655, 1.B.2)
P83. Temperate Andean evergreen forest of *Austrocedrus chilensis - Nothofagus dombeyi* (M655, 1.B.2)
P84. Temperate interior evergreen forest of *Nothofagus nitida - Podocarpus nubigenus* (M655, 1.B.2)
P85. Temperate interior evergreen forest of *Nothofagus betuloides / Desfontainia fulgens* (M658, 1.B.2)
P86. Temperate Andean evergreen forest of *Nothofagus betuloides - Laureliopsis philippiana* (M658, 1.B.2)
P87. Temperate Andean evergreen forest of *Nothofagus betuloides / Chusquea macrostachya* (M658, 1.B.2)
P88. Temperate Andean mixed forest of *Nothofagus betuloides / Berberis ilicifolia* (M658, 1.B.2)
P89. Temperate-Antiboreal Andean mixed forest of *Nothofagus betuloides - Nothofagus pumilio* (**, 1.B.2)
P90. Antiboreal coastal evergreen forest of *Nothofagus betuloides - Embothrium coccineum* (**, 1.B.2)
P91. Temperate-Antiboreal coastal evergreen forest of Nothofagus betuloides - Drimys winteri (**, 1.B.2)

Evergreen arborescent shrubland

P92. Temperate coastal evergreen shrubland of *Pilgerodendron uvifera - Nothofagus nitida* (***, 1.B.2)

Moorland

P93. Temperate coastal moorland of *Donatia fascicularis - Oreobolus obtusangulus* (M758, 2.C.2)
P94. Antiboreal coastal moorland of *Astelia pumila - Donatia fascicularis* (M759, 2.C.2)
P95. Temperate-Antiboreal coastal moorland of *Bolax caespitosus - Phyllachne uliginosa* (M759, 2.C.2)
P96. Temperate-Antiboreal interior moorland of *Sphagnum magellanicum / Schoenus antarcticus* (M759, 2.C.2)

High-Andean dwarf scrub

P97. Tropical Andean dwarf scrub of *Fabiana ramulosa - Diplostephium meyenii* (M794, 4.A.1)
P98. Tropical Andean dwarf scrub of *Parastrephia lucida - Azorella compacta* (M794, 4.A.1)
P99. Tropical Andean dwarf scrub of *Parastrephia lucida / Festuca orthophylla* (M794, 4.A.1)
P100. Tropical Andean dwarf scrub of *Parastrephia lepidophylla - P. qudrangularis* (M794, 4.A.1)
P101. Tropical Andean dwarf scrub of *Azorella compacta - Pycnophyllum molle* (M794, 4.A.1)
P102. Tropical Andean dwarf scrub of *Fabiana denudata - Chuquiraga atacamensis* (M794, 4.A.1)
P103. Tropical Andean dwarf scrub of *Fabiana squamata / Festuca chrysophylla* (M794, 4.A.1)
P104. Tropical Andean dwarf scrub of *Fabiana bryoides - Parastrephia quadrangularis* (M794, 4.A.1)
P105. Tropical Andean dwarf scrub of *Mulinum crassifolium - Urbania pappigera* (M794, 4.A.1)
P106. Tropical Andean dwarf scrub of *Artemisia copa / Jarava frigida* (M794, 4.A.1)
P107. Tropical Andean dwarf scrub of *Adesmia frigida / Jarava frigida* (M794, 4.A.1)
P108. Tropical-Mediterranean Andean dwarf scrub of *Adesmia hystrix - Ephedra breana* (M794, 4.A.1)
P109. Tropical-Mediterranean Andean dwarf scrub of *Adesmia subterranea - Adesmia echinus* (M794, 4.A.1)
P110. Mediterranean coastal dwarf scrub of *Chuquiraga oppositifolia - Mulinum spinosum* (M788, 3,B.1)
P111. Mediterranean Andean dwarf scrub of *Chuquiraga oppositifolia - Nardophyllum lanatum* (M788, 3,B.1)
P112. Mediterranean Andean dwarf scrub of *Laretia acaulis - Berberis empetrifolia* (M788, 3,B.1)
P113. Mediterranean Andean dwarf scrub of *Chuquiraga oppositifolia - Discaria articulata* (M788, 3,B.1)
P114. Temperate Andean dwarf scrub of *Discaria chacaye / Berberis empetrifolia* (M795, 4,B.1)
P115. Temperate Andean dwarf scrub of *Adesmia longipes - Senecio bipontinii* (M795, 4,B.1)
P116. Antiboreal Andean dwarf scrub of *Bolax gummifera - Azorella selago* (M796, 4,B.1)

High-Andean forb vegetation

P117. Tropical-Mediterranean Andean forb vegetation of *Chaetanthera sphaeroidalis* (M794, 4,A.1)
P118. Mediterranean Andean forb vegetation of *Nastanthus spathulatus - Menonvillea spathulata* (M788, 3,B.1)
P119. Mediterranean Andean forb vegetation of *Oxalis adenophylla - Pozoa coriacea* (M788, 3,B.1)
P120. Temperate Andean forb vegetation of *Nassauvia dentata - Senecio portalesianus* (M795, 4,B.1)
P121. Antiboreal Andean forb vegetation of *Nassauvia pygmaea - N. lagascae* (M796, 4,B.1)

Patagonian steppe and grasslands

P122. Mediterranean-Temperate eastern steppe of *Festuca pallescens / Mulinum spinosum* (M750, 2.B.2)
P123. Mediterranean eastern steppe of *Festuca gracillima* (M750, 2.B.2)
P124. Mediterranean eastern steppe of *Festuca gracillima / Mulinum spinosum* (M750, 2.B.2)
P125. Temperate eastern steppe of *Festuca gracillima / Chiliotrichum diffusum* (M750, 2.B.2)

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Supplementary material

Supplementary material 1
Formations, divisions and macrogroups represented in the Chilean intrazonal vegetation.
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